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The coupling between point-of-gaze and ball movements in three-ball cascade juggling: the effects of expertise, pattern and tempo

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The relationship between point-of-gaze and ball movements in three-ball juggling was examined as a function of expertise, pattern and tempo. Five intermediately skilled and five expert jugglers performed the standard and reverse cascade at three tempos, while point-of-gaze and ball movements were recorded simultaneously. Scaled to the size of the ball patterns, the experts made smaller point-of-gaze movements than the intermediates, especially in the horizontal direction and in the standard cascade. In both skill groups, point-of-gaze and ball movements were often 1:1 frequency locked in the horizontal direction, whereas in the vertical direction 1:2 frequency locking also occurred. In the latter direction, the 1:1 ratio prevailed in the intermediates and the 1:2 ratio in the experts. In addition, the incidence of the 1:1 ratio decreased and that of the 1:2 ratio increased with increasing tempo. Furthermore, in the vertical direction, increasing tempo resulted in a weaker 1:1 locking, whereas the strength of the 1:2 ratio remained unaffected by tempo. In the horizontal direction, the strength of the 1:1 locking was higher on average in the reverse cascade than in the standard cascade. We conclude that expertise in juggling is reflected by an overall reduction in the extent to which the balls are visually tracked, and that task constraints such as tempo and juggling pattern affect the visual search patterns of both expert and intermediate jugglers.

Keywords: eye-hand coordination, frequency locking, task constraints.

Introduction

Successful interceptive actions, such as hitting and catching, require the availability and pick-up of optical information about the spatial-temporal properties of the to-be-intercepted object. To obtain such optical information, the to-be-intercepted object is attended to visually. In general, however, visual attention is not restricted to this aspect of the environment, but may include other relevant aspects, such as support surfaces, parts of one's own body, other objects, team-mates, and so on. Even in circumstances that allow for the continuous tracking of an approaching object (e.g. catching, hitting), individuals do not continuously keep their eyes on the object (Goulet *et al.*, 1989; Abernethy, 1990; Amazeen *et al.*, 2001). Instead, they tend to look at only

a part of the trajectory. Apparently, such trajectory segments contain sufficient information about the future position of the object to intercept it successfully.

It is widely recognized that the pick-up of information is an activity that has to be acquired and, as such, is based on experience rather than innate mechanisms (even though the prerequisite sensory machinery is largely innate). According to Gibson and Gibson (1955), perceptual learning is based on the 'education of attention' – that is, the attunement of perceptual systems to the most useful or essential information for performing a certain task. The notion of 'education of attention' is closely allied to that of 'perceptual differentiation', according to which an observer learns to differentiate between the sources of information that are available to him or her in the various perceptual arrays. The notion of 'perceptual differentiation' stands in contrast to the notion of 'perceptual enrichment', which holds that an observer learns to perceive by building more elaborate and precise internal representations for

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constructing percepts from sense data. The education of attention and perceptual differentiation may be beneficial for performance in two regards. First, more information may be extracted from the same event, leaving visual search unaffected. Second, useful information may be picked up from objects or events that was not picked up before, possibly accompanied by different patterns of visual search.

It is apparent from possibilities such as these that visual search patterns provide an expedient window into the study of the performance and acquisition of perceptual-motor tasks. Patterns of visual search vary systematically as a function of expertise and task constraints, such as variations in speed and performance instructions (Epelboim, 1998; Amazeen *et al.*, 2001). Analyses of visual search patterns may, therefore, provide important clues about the organization of perceptual-motor tasks, their perceptual basis and the process of skill acquisition. In the present study, we examine the relationship between point-of-gaze and ball movements in cascade juggling as a function of expertise, tempo and pattern to elucidate these issues in the context of a perceptual-motor activity that allows for the application of advanced tools for the analysis of time series and their correlation. Before introducing the expectations that motivated the present experiment, it is useful to discuss briefly the effects of both expertise and task constraints on visual search, to clarify our methodological position and to summarize previous research on cascade juggling from our laboratory bearing on the perceptual basis of juggling.

Effect of expertise on visual search

Apart from the quality and accuracy of perceptual judgements, differences in the perceptual skills of expert and non-expert performers manifest themselves as differences in visual search behaviour (Williams *et al.*, 1992; Bard *et al.*, 1994; Ripoll *et al.*, 1995; Helsen and Starkes, 1999; Amazeen *et al.*, 2001). In general, visual search patterns of expert performers appear to be characterized by earlier information pick-up (implying that information is being picked up from earlier phases of an unfolding event, such as a ball travelling through the air) and fewer fixations of longer duration. Making fewer fixations of longer duration is considered effective because the sensitivity of the visual system is strongly reduced during saccades (Williams *et al.*, 1993).

Abernethy (1990) and Abernethy and Russell (1987), who respectively studied the ability of squash and badminton players to predict the direction and force of an opponent's stroke and its landing position, found that the visual search patterns of experts and non-experts were indistinguishable, even though the perceptual judgements of the experts were clearly

superior to those of the non-experts. These authors concluded that experts differ primarily from non-experts in their ability to make full use of the available information, an interpretation that is consistent with the Gibsonian idea of perceptual differentiation but which de-emphasizes the importance of visual search behaviour.

Perceptual differentiation may also lead to shifts in the relative importance of the different perceptual modalities involved in the performance of a task, which, in turn, may be reflected in the manner in which a particular task is performed (Fleishman, 1962; Fitts, 1965; Adams *et al.*, 1977; Proteau, 1992). For instance, in a classical experiment on the acquisition of a two-handed coordination task, Fleishman and Rich (1963) showed that vision was more important in the early than later stages of learning. Kinaesthesia, on the other hand, became more important as skill increased and 'kinaesthetic ability' was found to be a better predictor for learning in the long run. In a similar spirit, Henderson (1975) showed that experts are more sensitive to kinaesthetic information than non-experts. She had expert and non-expert performers predict the outcome of dart throws in an experimental set-up in which the flight of the dart was obscured immediately after its release. The required predictions thus had to be made solely on the basis of kinaesthetic information. The expert dart players were clearly better at this task than the non-expert dart players. Consistent with the insights of Fleishman and Rich (1963), Henderson (1975) concluded from this finding that the expert dart players possessed better kinaesthetic abilities than the non-expert dart players and thus relied more on kinaesthetic than on optical information.

An opposite effect was reported by Proteau *et al.* (1987), who showed that, in manual aiming tasks, removal of visual feedback of the moving limb has less detrimental consequences early in practice than later in practice. In other occlusion studies, however, removal of vision significantly increased the movement time required by novices to cross a beam, whereas this manipulation had no effect in expert gymnasts (Robertson *et al.*, 1994). In a similar vein, Fischman and Schneider (1985) showed that preventing sight of the catching hand was less detrimental to performance in skilled catchers than in unskilled catchers.

In summary, task-specific constraints determine the relative importance of different perceptual modalities during various stages of learning. Although the implications of this general conclusion for visual search behaviour have not been studied to date, it is likely that shifts in the amount of reliance on vision versus kinaesthesia (such as expected in juggling; see later) will be accompanied by changes in visual search behaviour.

Effects of task constraints on visual search

The task constraints define what optical information is useful and thus which patterns of visual search will be effective in finding and picking up this information. Temporal constraints are known to affect visual search behaviour. For instance, in repeatedly catching and throwing a (single) ball, the line of gaze of participants intersected the ball at an earlier phase of the ball flight relative to the zenith when tempo of performance was higher (Amazeen *et al.*, 2001).

Besides temporal constraints, the number of relevant elements or objects in a task may affect visual search behaviour. Tasks involving multiple elements require the distribution of visual attention, especially if their configuration is changing. In cases like this, the (continuously changing) temporal-spatial relations between the elements determine which information has to be picked up and which visual search pattern will be the most effective for doing so. For instance, in soccer, in one-against-one and eleven-against-eleven situations, the more effective search (exhibited by the experts) is characterized by making more fixations of shorter duration (Williams *et al.*, 1994; Williams and Davids, 1998). This is at odds with typical findings regarding visual search in experts, but is fully understandable from the prevailing task constraints. Other factors that have been shown to influence visual search are anxiety (in karate; Williams and Elliott, 1999) and age (Bard and Fleury, 1981).

Methodological position

Despite the increased interest of researchers in studying the relation between perception and action using 'ecologically valid' methods (Abernethy, 1991; Williams *et al.*, 1992), there is still a paucity of research on visual search that explicitly addresses the coupling between perception and action. This is unfortunate, because patterns of visual search are likely to depend on the activity they support. For instance, Milner and Goodale (1995) have presented convincing physiological and behavioural evidence for the existence of two separate visual systems, one subserving the performance of motor actions, the other subserving 'judgemental seeing'. From a practical point of view, this implies, for instance, that looking at an approaching tennis ball to judge where it will land might involve a different system than looking at a ball with the aim to return it, and thus might be accompanied by different search patterns. In view of such theoretical considerations, it seems appropriate to study visual search for action in close conjunction with the action that it supports.

Although there has been some research focusing on the coupling between point-of-gaze and hand move-

ments in the context of aiming tasks (e.g. Prablanc *et al.*, 1986; Helsen *et al.*, 1998), the methods used in these studies have been restricted to the analysis of discrete temporal events, such as the initiation of the gaze shift relative to that of the hand movement, the moment of peak velocity of the hand and the moment that the line of gaze makes contact with the object relative to the hand. Perhaps because of the discrete nature of goal-directed aiming tasks, the application of time series analysis techniques that are particularly well suited to study the interaction between dynamical subsystems has been limited in this line of research. These techniques are expedient tools for studying the time-continuous coupling between action and perception and thus for gaining insight into the manner in which patterns of visual search are embedded in the performance of perceptual-motor tasks. Rhythmic, repetitive tasks more readily allow for the application of time series analysis techniques than discrete tasks and appear, therefore, to be especially suited for studying visual search behaviour in relation to on-line task performance. An example of such a task is (cascade) juggling. The cyclic, repetitive nature of this activity allows for studying the time-continuous coupling of relevant subsystems, such as patterns of visual search and ball and hand movements. Furthermore, juggling involves the manipulation of multiple elements (balls), meaning that visual attention has to be divided, as optical information has to be picked up about each thrown ball. Finally, juggling is a task that requires considerable practice, thus allowing for an assessment of the effects of expertise over a broad range of abilities.

Juggling and visual search

In three-ball cascade juggling, the balls are thrown and caught with a phase lag of approximately $2\pi/3$ rad. During the time one ball completes one cycle in the horizontal direction (e.g. from a throw of the right hand to the next throw of the right hand of the same ball), it completes two cycles in the vertical direction, thereby establishing a 1:2 frequency ratio between the x and y components of the ball movements.

Because it is impossible to keep an eye on all balls at all times, visual attention has to be divided. In an attempt to reveal which part of the ball trajectory jugglers prefer to look at, Van Santvoord and Beek (1994) introduced a temporal occlusion method that allowed the jugglers to self-select the moments of (no-) occlusion. Jugglers of intermediate skill juggled a three-ball standard cascade pattern while wearing liquid crystal glasses that opened and closed rhythmically, thereby allowing intermittent viewing. By adjusting the frequency and the phasing of juggling to the opening and closing of the glasses, the jugglers themselves could

select the part of the ball trajectory they preferred to look at. In some trials, participants achieved phase locking between the rhythm of opening and closing of the glasses and the ball trajectories. In these trials, less temporal variability between consecutive catches, zeniths and throws was observed than in trials in which phase locking was absent. In the phase-locked trials, a preference was observed to time the juggle in a way that allowed viewing the balls just after they had passed the zenith. Although this finding may be taken to suggest that the zenith is of special significance, it is important to note that Van Santvoord and Beek (1994) did not manipulate the frequency of the intermittent viewing interval; perhaps other parts of the ball trajectories would have been preferred at other tempos. Moreover, in trials in which no phase locking occurred and many segments of the ball flight were visible, the juggle could still be sustained. A drawback of the method used was that it provided no information about direction of gaze. Thus, it could not be established whether point-of-gaze was also locked to the ball movements.

There are indications that expertise affects visual search behaviour in juggling. Although anecdotal, in the course of learning to juggle, jugglers often develop what they call a gaze-through or distant stare. In the gaze-through, the line of gaze stays bounded within a small, but economically chosen, region of the pattern. The development of a gaze-through suggests at least some decoupling of direction of gaze and ball movements. In all likelihood, jugglers with a gaze-through rely more on peripheral vision and kinaesthetic and haptic information than on foveal vision. How the relative importance of these perceptual modalities evolves in the course of learning, however, is unknown. Although peripheral vision plays an important role in motion detection (Abernethy, 1991; Williams *et al.*, 1992), it is also the case that some expert jugglers can juggle blindfolded.

In summary, the zeniths of the ball trajectories are proposed to contain important, albeit not strictly necessary, information for juggling. Frequency and phase locking between the ball movements and the corresponding optical information pick-up may occur, although mode locking between point-of-gaze and ball movements has not yet been demonstrated. Anecdotal observations suggest that the organization of visual search of expert jugglers may be characterized by a decoupling of point-of-gaze and ball movements.

Experimental expectations

The experiment reported here was conducted to examine the validity of the following three expectations. First, in line with previous findings in and outside the

context of juggling, we expected greater expertise to result in more economical (i.e. smaller, more confined) visual search patterns, earlier visual contact with the ball (if any) and weaker coupling between point-of-gaze and ball movements. Second, we expected that higher tempos of performance would lead to a weaker coupling between point-of-gaze and ball movements as well as to visual contact with the ball at earlier phases of its flight (if any). The first part of this second expectation was based on the well-documented observation that increasing frequency resulted in weaker mode locking in a variety of bimanual coordination tasks (Kelso, 1995; Peper *et al.*, 1995). Finally, we expected that the reverse cascade, which is more difficult than the standard cascade and therefore presumably more dependent on the pick-up of accurate optical information, would result in a stronger coupling between point-of-gaze and ball movements.

Methods

Participants

Five intermediate (four male, one female) and five expert jugglers (all male) participated after having provided informed consent. They were aged 19–42 years (mean = 31.1 years). All but one of the participants were self-confessed right-handers. Expert jugglers were defined as those who could juggle five or more balls. Intermediate jugglers were defined as those who could comfortably maintain a three-ball juggle; one of the intermediate jugglers was able to perform a solid four-ball juggle.

Apparatus

Each trial was videotaped using a 50 Hz video camera, which was placed 4 m in front of the participants. All juggles were performed with three plastic 'stage balls' with a diameter of 7.3 cm and a mass of 130 g.

The line of gaze was monitored continuously with an eye-tracking system (Applied Science Laboratories, Series 4000 Eye Tracker, 50 Hz, spatial accuracy 0.6°) mounted on a lightweight helmet (constructed by Mooij Holding B.V.). The helmet was equipped with a video camera (EMLO CCD Color Camera, Model MP481, 50 Hz, 90° lens), which recorded the scene from the juggler's perspective. A cursor was superimposed on the recorded scene, which indicated the line of gaze. The eye tracker was calibrated (using a nine-point calibration frame) before each participant started performing the experimental trials. Synchronization of video-recordings and the gaze-tracking data was achieved by a control unit with a time-code generator,

which time-stamped both the video-recordings and the gaze-tracker data.

Procedure

The experiment consisted of six trials of 1 min duration. In particular, the standard cascade (SC) and the reverse cascade (RC; see Fig. 1) were juggled at three tempos: preferred, slow and fast. Specific tempos could have been imposed by using a metronome indicating the moments of throwing or catching, or a visual target indicating how high the balls had to be thrown (corresponding roughly to juggling tempo). Both methods, however, would have had the drawback of introducing additional task constraints, which might have interfered with ‘natural’ task performance. Therefore, the jugglers were asked to self-select the three tempos. Two of the intermediates were not able to juggle the reverse cascade at the required tempo conditions.

Data reduction and analysis

The horizontal and vertical displacements of the balls were digitized (using the WinAnalyse software package, Mikromak) from the floor-mounted video-recordings. The recordings from the head-mounted camera were coded so as to obtain time series indicating when the line of gaze intersected with each ball. These time series consisted of the spatial orientation of the ball and gaze when the two intersected and the pixel coordinates (0,0) when they did not intersect. The first full juggling cycle was removed from all time series to eliminate possible transient effects associated with the start-up of the juggle. At the start of a trial, all participants made relatively large point-of-gaze movements. In some trials, a sudden, marked drop in the amplitude of the point-of-gaze movements occurred after this initial, transient phase, resulting in a distant stare (see Fig. 2). If present, this marked change was used to visually determine the

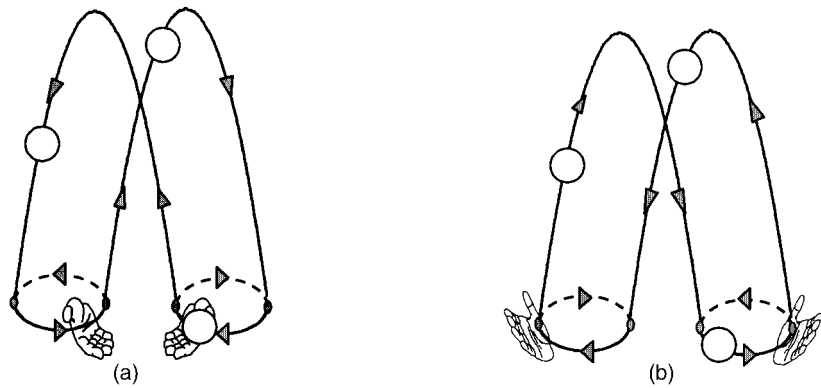


Fig. 1. Schematic representation of the standard cascade (a) and reverse cascade (b). The hands indicate the locations of throwing.

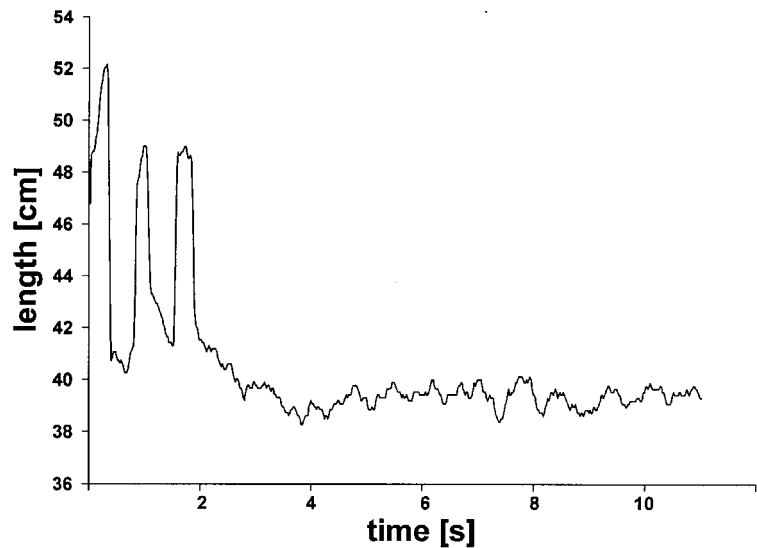


Fig. 2. Example of point-of-gaze settling into a distant stare.

onset of the distant stare. If the distant stare lasted at least half the duration of the time series, the part of the time series before the onset of the distant stare was removed. This occurred in four trials and resulted in the removal of approximately 8.0, 6.2, 10.8 and 1.4 s of data in those trials, respectively. Finally, at the end of the time series, a few data points were removed to ensure maximal periodicity and optimal synchronization between the time series corresponding to a trial (i.e. the time series of the first ball started and ended with equal phasing and the time series of the other events started and ended at the same real time).

The horizontal and vertical changes in the direction of gaze were analysed separately. The rationale for this partitioning was two-fold. First, neurophysiological as well as functional evidence suggests that eye movements are organized in two separate dimensions, horizontal and vertical. In addition to the well-established differential brainstem pathways that are involved in the production and control of horizontal and vertical eye movements, be they saccades or smooth pursuit tracking movements (Wirtschafter and Weingarden, 1988), the velocity profiles of the orthogonal components of oblique saccades are only weakly correlated (Becker and Jürgens, 1990). Thus, the (at least partial) independence of the control processes involved may lead to different kinematics of the two components. Similar conclusions were reached regarding smooth pursuit eye movements, which also revealed upward-downward asymmetries in the vertical direction (Rottach *et al.*, 1996). Second, in addition to the differential task-related dynamics of juggling in the horizontal and vertical direction (see above), the active constraints in both orthogonal components are markedly different in that the gravitational force constrains the time evolution of the balls in the vertical, but not in the horizontal, direction.

The amplitude of the point-of-gaze movements was computed for both the horizontal and vertical direction using a peak-finding algorithm. From the time derivative of the vertical displacement of the balls, using a five-point difference method (Lees, 1980), the temporal locations of the throws were estimated using the moment of maximal velocity as the criterion. After having established the zeniths with a peak-finding algorithm, the height (h) of each throw, defined as the vertical distance from the location of the throw to its zenith, was calculated. In addition, the horizontal distance between each pair of consecutive zeniths (D) was calculated. Subsequently, within-trial means of these spatial variables were calculated. The average amplitude of the point-of-gaze movements in the horizontal direction was normalized with respect to the average distance between the zeniths (D). In the vertical direction, the average amplitude of the point-of-gaze

movements was normalized with respect to the average height of the throws (h).

Spectral analysis was performed on all the position time series of point-of-gaze and ball movements. The spectral estimates of the three balls were nearly identical in each direction; we therefore averaged these spectral estimates to obtain a single spectral estimate for the balls in both the horizontal and vertical direction for each trial. All spectral estimates were normalized by dividing them by the variance of the time series, and the frequency with the largest power was determined for each trial. These (main) frequencies are denoted by ω . Subsequently, the frequency ratios between point-of-gaze and ball movements in the horizontal and vertical direction were obtained by dividing the frequency of one series by the frequency of the other.

As a measure for the strength of the frequency locking between point-of-gaze and ball movements in each direction, we calculated the scaled cross-integral of two spectral density estimates using the equation:

$$\psi_{x,y}(r) = 2 \times \frac{\int P_x(f) \times P_y(f \times r) df}{\int [P_x(f)^2 + P_y(f \times r)^2] df}$$

where P_x and P_y represent the spectral density estimates of the time series of $x(t)$ and $y(t)$, as a function of frequency (f). The scaling ratio (r) was assigned the value of the frequency-locked ratio. The more similar two spectra are over the entire frequency band, the higher the scaled cross-integral ($\psi_{x,y}$). Due to the normalization, it is bounded between 0 and 1, indicating the minimal and maximal frequency locking strength, respectively (for documentation of this measure, see Daffertshofer *et al.*, 2000).

Finally, the following variables were calculated from the newly obtained time series of the balls and those indicating the intersection of the line of gaze and the balls: phase (θ), time to catch, time on ball and percentage of intersections. The phase (θ_i) denotes the point estimate of the phase of the ball in the vertical direction (at cycle i) at the first moment the line of gaze intersected with that particular ball. Phase was calculated using the equation:

$$\theta_{(i)} = \frac{t_{\text{zenith}(i)} - t_{\text{intersection}(i)}}{T_{(i)}} \times 2\pi$$

where $t_{\text{zenith}(i)}$ refers to the instant the ball was at the zenith, $t_{\text{intersection}(i)}$ to the instant the line of gaze intersected with the ball and $T_{(i)}$ to the period of the ball cycle in the vertical direction. The phase provides a measure of the spatial location along the ball's trajectory in the vertical direction. Positive values indicate that the

intersection occurred before the zenith. Time to catch refers to the time interval between the first moment of intersection of the line of gaze with the ball trajectory after the toss and the subsequent catch. Time on ball indicates the amount of time that the line of gaze intersected with the ball. This duration is expressed as a percentage of the period of the ball, T_i . The line of gaze did not intersect with the ball during each toss. Therefore, the percentage of intersections was calculated, defined as the number of times the line of gaze intersected with the balls divided by the number of ball cycles multiplied by 100. This variable can be taken as a measure indicating to what extent detailed information was picked up (since visual acuity is only high in the foveal area). Of course, phase (θ), time to catch and time on ball could only be calculated when there was an intersection between the line of gaze and one of the balls.

Repeated-measures analyses of variance were performed according to a $2 \times 2 \times 3$ factorial design using expertise (intermediate, expert) as a between-participants factor and pattern (standard, reverse) and tempo (preferred, slow, fast) as within-participant factors. The following variables were subjected to statistical analysis: the frequency of the balls (in the vertical direction), distance between the zeniths (D), height of the throws (h), amplitude of the point-of-gaze movements (x and y), frequency locking strength (x and y), phase (θ), time to catch, time on ball and percentage of intersections.

Results

Figure 3 gives an impression of the data. Time series of the point-of-gaze and ball movements are shown for each of the two juggling patterns, as performed by an intermediate and an expert juggler.

Ball movements

As a first step in the analysis of the data, we examined whether the tempo instruction was fulfilled. The analysis of variance (ANOVA) on ball frequency in the vertical direction revealed a main effect of tempo ($F_{2,16} = 141$, $P = 0.001$, $\omega_{\text{slow}} = 4.78 \pm 0.94 \text{ rad} \cdot \text{s}^{-1}$, $\omega_{\text{preferred}} = 7.10 \pm 1.29 \text{ rad} \cdot \text{s}^{-1}$, $\omega_{\text{fast}} = 8.42 \pm 1.33 \text{ rad} \cdot \text{s}^{-1}$; mean \pm s). *Post-hoc* comparisons (Newman-Keuls, $\alpha = 0.05$) showed that the three tempo conditions were indeed juggled at different tempos. A significant interaction between tempo and expertise ($F_{2,16} = 5.19$, $P = 0.05$) revealed that the experts juggled slower in the slow condition and faster in the fast condition than the intermediates, although across tempo condition the two skill groups' juggling frequency did not differ significantly ($F_{1,2} = 0.214$, $P = 0.65$). Moreover, inspection of the data revealed that, within each individual, the condition $\omega_{\text{slow}} < \omega_{\text{preferred}} < \omega_{\text{fast}}$ was met in each of the two juggling patterns (if applicable). Finally, the narrow peaks in the spectral estimates of the ball movements suggested that all trials were juggled with minimal variation in frequency.

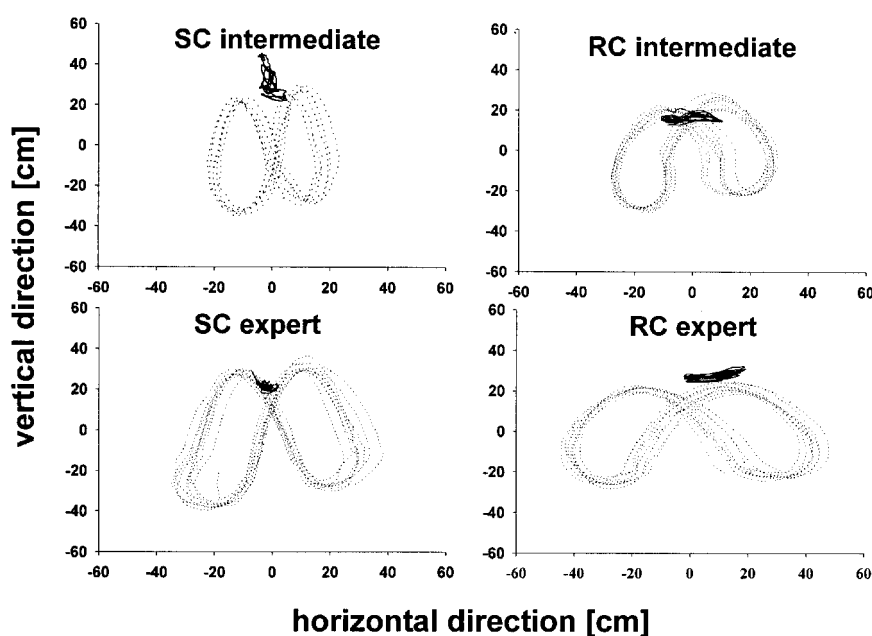


Fig. 3. Examples of point-of-gaze (solid lines) and ball trajectories (dotted lines) for an intermediate and an expert juggler, performing both the standard cascade (SC) and the reverse cascade (RC), for six full cycles of the balls in the vertical direction.

Since the label 'expert' as such does not guarantee excellent performance, we checked whether the experts indeed performed better than the intermediates. Quality of performance was operationalized in terms of juggling cycle variability: the smaller this variability, the better the performance. Juggling cycle variability was operationalized as the mean of the scaled cross-integrals ($\psi_{x,y}$) at a 1:1 frequency ratio between the trajectories of the three balls in both directions (e.g. the mean of $\psi_{b1x,b2x}$, $\psi_{b1x,b3x}$, $\psi_{b2x,b3x}$, $\psi_{b1y,b2y}$, $\psi_{b1y,b3y}$ and $\psi_{b2y,b3y}$). According to this measure, the experts juggled significantly better than the intermediates (main effect for expertise: $F_{1,8} = 15.0$, $P = 0.005$; experts = 1.000 ± 0.001 , intermediates = 0.988 ± 0.002). The main effect for tempo was almost significant ($F_{2,16} = 3.50$, $P = 0.055$), as performance tended to be better in the preferred conditions than in the other conditions. In addition, there was a significant interaction between pattern and tempo ($F_{2,16} = 4.80$, $P = 0.023$) because a lower tempo had only a detrimental effect on performance in the standard cascade. Finally, there was a significant interaction between expertise and tempo ($F_{2,16} = 4.00$, $P = 0.039$) because, in contrast to the experts, the intermediates performed worse in the slow and fast conditions than in the preferred tempo condition (experts: slow = 1.000 ± 0.000 , preferred = 0.999 ± 0.000 , fast = 1.000 ± 0.001 ; intermediates: slow = 0.997 ± 0.002 , preferred = 0.999 ± 0.001 , fast = 0.997 ± 0.002).

To compare the spatial properties of the standard and the reverse cascade, a repeated-measures ANOVA was performed on the average distance between the zeniths (D) and the average height of the throws (h). For the average distance between the zeniths, there was a significant main effect of pattern ($F_{1,8} = 13.3$, $P = 0.008$) (standard cascade = 18.9 ± 4.31 cm, reverse cascade = 22.3 ± 7.43 cm). Furthermore, there were significant main effects of tempo ($F_{2,16} = 20.6$, $P = 0.001$) (24.2 ± 6.31 , 20.9 ± 5.45 and 16.8 ± 4.83 cm for the slow, preferred and fast conditions respectively) and expertise ($F_{1,8} = 13.8$, $P = 0.007$) (experts = 23.4 ± 6.8 cm, intermediates = 17.8 ± 4.2 cm). There was also a significant interaction between pattern and expertise ($F_{1,8} = 6.65$, $P = 0.034$), because only in the experts was the average distance between the zeniths larger in the reverse cascade than in the standard cascade.

For the average height of the throws, there was a significant main effect of pattern ($F_{1,8} = 5.48$, $P = 0.048$) because the balls were thrown higher in the standard cascade (36.8 ± 22.0 cm) than in the reverse cascade (29.0 ± 14.8 cm). As expected, there was also a significant main effect of tempo ($F_{2,16} = 117$, $P = 0.001$) (52.1 ± 17.0 , 28.3 ± 12.5 and 18.3 ± 6.5 cm for the slow, preferred and fast conditions respectively). Finally, there was a significant interaction between tempo and

expertise ($F_{2,16} = 6.42$, $P = 0.001$) (consistent with the statistical results for ball frequency) and between pattern and tempo ($F_{2,16} = 5.71$, $P = 0.014$). The latter interaction occurred because the tempo effect was more pronounced in the standard cascade. In summary, the reverse cascade was more elongated in the horizontal direction and less elongated in the vertical direction than the standard cascade.

Point-of-gaze movements

A repeated-measures ANOVA on the normalized amplitude of the point-of-gaze movements in the horizontal direction revealed a significant main effect of pattern ($F_{1,8} = 34.8$, $P = 0.001$) (standard cascade = 0.24 ± 0.21 , reverse cascade = 0.73 ± 0.35). Although tempo failed to reach significance ($F_{2,16} = 3.27$, $P = 0.066$), the point-of-gaze amplitude tended to be larger in the slow condition (slow = 0.55 ± 0.33 , preferred = 0.44 ± 0.35 , fast = 0.45 ± 0.43). Expertise also failed to reach significance ($F_{1,8} = 3.35$, $P = 0.105$), although the experts made smaller point-of-gaze movements than the intermediates (experts = 0.37 ± 0.35 , intermediates = 0.60 ± 0.37). The interaction between tempo and expertise ($F_{2,16} = 5.52$, $P = 0.05$) showed that the normalized amplitude of the point-of-gaze movements of the experts decreased significantly as juggling speed increased, whereas this effect was absent in the intermediates (experts: slow = 0.53 ± 0.38 , preferred = 0.29 ± 0.30 , fast = 0.29 ± 0.29 ; intermediates: slow = 0.58 ± 0.28 , preferred = 0.59 ± 0.33 , fast = 0.62 ± 0.30). In the vertical direction, the only significant main effect was that of pattern ($F_{1,8} = 7.99$, $P = 0.05$) (standard cascade = 0.13 ± 0.08 , reverse cascade = 0.20 ± 0.09). Hence, regardless of the (spatial) dimensions of the juggling patterns, the reverse cascade elicited larger point-of-gaze movements in both directions.

Coordination between point-of-gaze and ball movements

When examining the frequency relation between the point-of-gaze and ball movements in the present experiment, it is important to note that three balls had to be tracked by one pair of eyes. Therefore, we rescaled any observed $p:q$ frequency ratio between the temporal evolution of the direction of gaze and the movement of each ball in both directions to $p:3q$. A 3:1 frequency locking between the point-of-gaze movements and the movement of a single ball implies that a gaze shift was made towards each ball. A 1:1 frequency locking between point-of-gaze and ball movements was accepted if the main frequency of the point-of-gaze movements divided by three times the main frequency of the ball movements was close to 1 – that is, $\max(P_{\text{gaze}})/3 \cdot \max(P_{\text{ball}}) \approx 1$.

In the horizontal direction, there was a 1 : 1 frequency locking between point-of-gaze and ball movements in 46 of the 54 trials (85%; see Fig. 4). The presence of a 1 : 1 locking mode indicates that every ball cycle was accompanied by a point-of-gaze cycle. In the remaining trials, no frequency locking was apparent. Overall, the intermediates recorded more incidences of 1 : 1 frequency locking than the experts (92% *vs* 80%).

The strength of the 1:1 frequency locking (see Fig. 5), as indexed by the scaled cross-integral,

depended on pattern ($F_{1,8} = 9.08, P = 0.018$; standard cascade = 0.58 ± 0.22 , reverse cascade = 0.71 ± 0.15). The interaction between pattern and tempo ($F_{2,16} = 3.34, P = 0.062$) suggested a tendency for locking strength to decrease as tempo increased for the standard cascade, which was not the case for the reverse cascade.

In 64% of all trials, the point-of-gaze and ball movements were frequency locked in the vertical direction. Two modes of frequency locking occurred equally often (see Fig. 6), 1 : 1 (33%) and 1 : 2 (31%). Figure 7

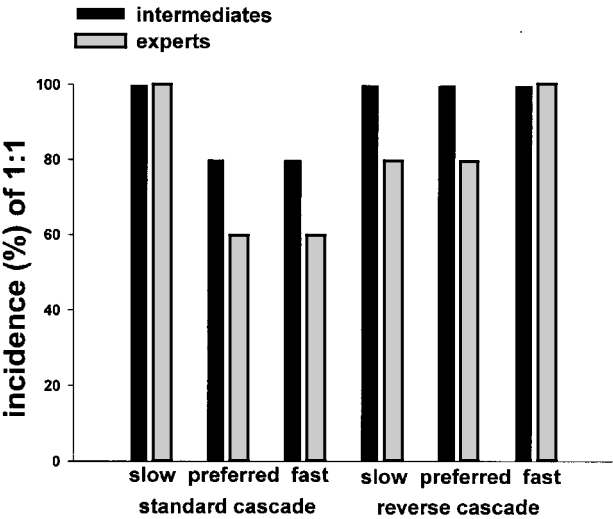


Fig. 4. Incidence (%) of 1:1 frequency locking between point-of-gaze and ball movements in the horizontal direction as a function of pattern, tempo and expertise.

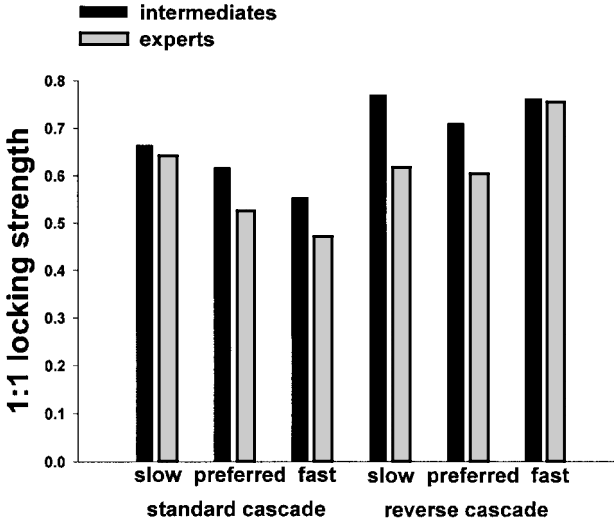


Fig. 5. Strength of 1:1 frequency locking between point-of-gaze and ball movements in the horizontal direction as a function of pattern, tempo and expertise.

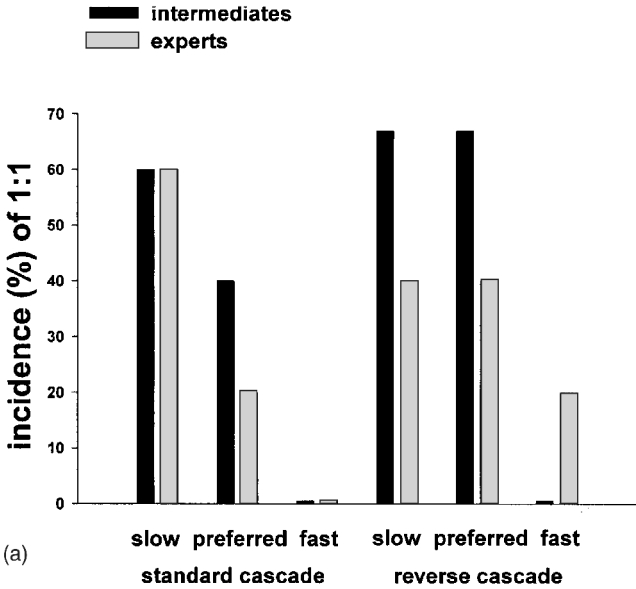


Fig. 6. Incidence (%) of 1:1 frequency locking (a) and 1:2 frequency locking (b) between point-of-gaze and ball movements in the vertical direction as a function of pattern, tempo and expertise.

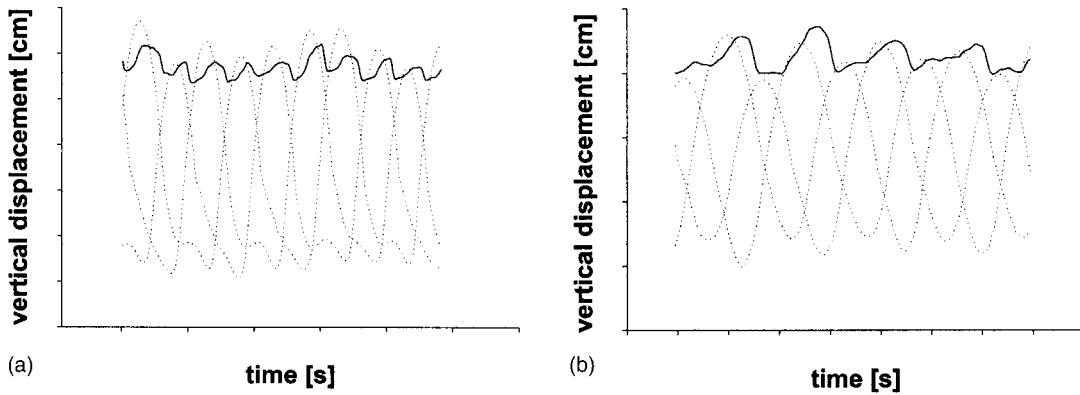


Fig. 7. Example of point-of-gaze (solid line) and ball movements (dotted lines) in the vertical direction exhibiting 1 : 1 frequency locking (a) and 1 : 2 frequency locking (b).

illustrates these 1 : 1 and 1 : 2 mode locking behaviours. As one can see from this figure, the direct 1 : 1 frequency coordination between point-of-gaze and ball movements was abandoned in the 1 : 2 mode.

In the slow tempo condition, the 1 : 1 locking mode prevailed, whereas the 1 : 2 locking mode prevailed at the highest juggling frequencies. A 1 : 1 frequency locking was observed in 56%, 39% and 6% of the slow, preferred and fast trials respectively. For the 1 : 2 frequency locking, the figures were 22%, 33% and 39% respectively. The experts recorded more instances of 1 : 2 locking than the intermediates (37% *vs* 30%) and fewer instances of 1 : 1 frequencylocking (25% *vs* 38%). For the locking strength of the 1 : 1 locking ratio, there was a significant main effect of tempo ($F_{2,16} = 17.8$, $P = 0.001$; see Fig. 8). As tempo increased, locking strength decreased: 0.47 ± 0.27 , 0.27 ± 0.23 and 0.11 ± 0.11 for the slow, preferred and fast tempo conditions respectively. As for the 1 : 2 locking mode, no significant effect of tempo was seen.

Subsequently, we determined whether there was a relation between the normalized amplitude of the point-of-gaze movements and locking strength. Except for very small gaze shifts, locking strength was independent of the normalized amplitude of the point-of-gaze movements in the horizontal direction; locking strengths between 0.6 and 0.8 were mainly observed (see Fig. 9). A broader range of locking strengths was observed in trials in which the gaze shifts were very small. Only the experts showed strong frequency locking while making very small gaze shifts. This was mainly observed during the standard cascade and only in a limited number of trials.

Figure 10 shows the relation between the normalized amplitude of the point-of-gaze movements and locking strength in the vertical direction. For locking strength, the value of the identified frequency-locked ratio was

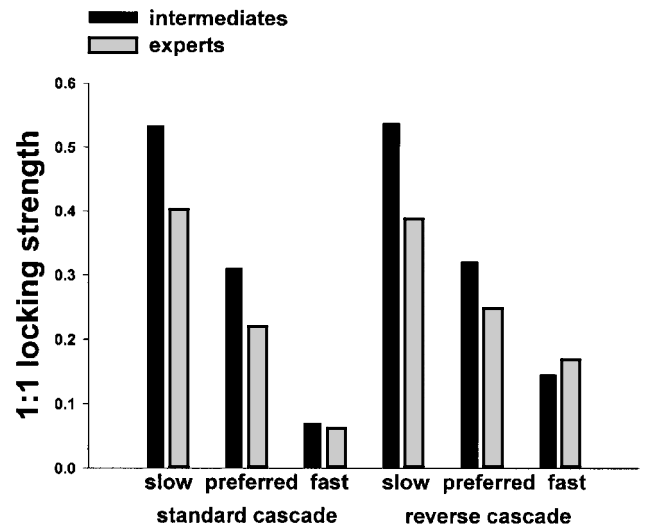


Fig. 8. Strength of 1 : 1 frequency locking between point-of-gaze and ball movements in the vertical direction as a function of pattern, tempo and expertise.

selected. When no locking was observed, the highest value of the two frequency ratios (i.e. 1 : 1 and 1 : 2) was chosen. Although the scatter plot shows a large dispersion, the normalized amplitude of the point-of-gaze movements and locking strength appeared to be linearly related in the vertical direction. (For both directions, the same plots were made using the real length of the point-of-gaze movements. This did not alter the form of the plots.)

Finally, the timing characteristics of the intersection of the line of gaze and the balls were subjected to repeated-measures analyses of variance. With regard to the phase (θ), a significant main effect of pattern ($F_{1,8} = 41.0$, $P = 0.001$) was noted because the line of gaze intersected with the ball flight earlier in the standard

than in the reverse cascade (0.80 ± 0.66 vs 0.0 ± 0.35 rad). For the time to catch, a significant main effect of pattern ($F_{1,8} = 41.5$, $P = 0.001$) was recorded because the time interval between the first intersection of the line of gaze with the ball trajectory after the toss and the subsequent catch was significantly longer in the standard than in the reverse cascade (471 ± 110 vs 357 ± 86 ms). In addition, a main effect of tempo ($F_{2,16} = 20.0$, $P = 0.001$) was seen because of a decrease in this time window with increasing juggling frequency (slow = 472 ± 102 ms, preferred = 357 ± 95 ms, fast =

331 ± 101 ms). The significant main effect of pattern ($F_{1,8} = 6.82$, $P = 0.049$) showed that the percentage of intersections between the line of gaze and the balls was significantly lower in the standard than in the reverse cascade ($50.0 \pm 21.0\%$ vs $63.0 \pm 30.6\%$). The effect of tempo just failed to reach significance ($F_{2,16} = 3.49$, $P = 0.056$); there tended to be more intersections in the slow condition than in the faster conditions. The effect of expertise did not reach significance either ($F_{1,8} = 3.42$, $P = 0.10$), although the experts ($46.0 \pm 25.6\%$) showed a tendency to intersect their line of gaze with the balls less often than the intermediates ($67.0 \pm 24.2\%$). There was a significant interaction between tempo and expertise ($F_{2,16} = 5.15$, $P = 0.020$) because in all tempo conditions except the fast condition the experts intersected their line of gaze less often with the balls than the intermediates. A main effect of tempo ($F_{2,16} = 38.2$, $P = 0.001$) on relative time on ball showed that, the higher the tempo, the longer the point-of-gaze dwelled on the balls (slow = 8.2 ± 3.6 , preferred = 12.8 ± 4.3 , fast = 16.9 ± 3.9). There was a marginally significant interaction between tempo and expertise ($F_{2,16} = 3.24$, $P = 0.066$) because the effect of tempo tended to be more pronounced in the experts.

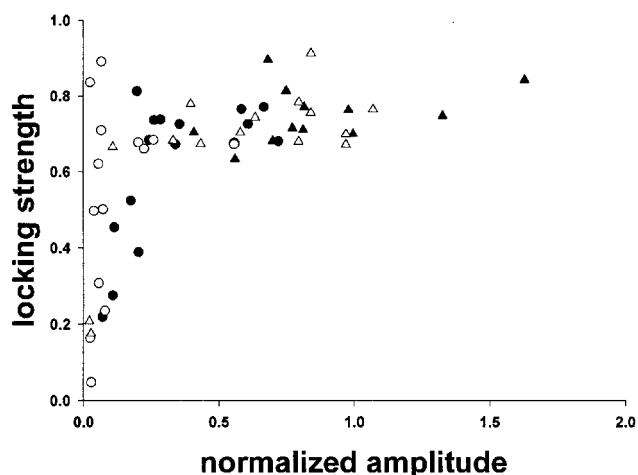


Fig. 9. Relation between the normalized amplitude of point-of-gaze movements and strength of frequency locking in the horizontal direction as a function of expertise and pattern (in dimensionless units). Standard cascade represented by circles, reverse cascade by triangles. Intermediates represented by solid symbols, experts represented by open symbols.

General discussion

The aim of the present experiment was to examine the relationship between point-of-gaze and ball movements in three-ball cascade juggling to elucidate how visual search is affected by expertise as well as task parameters such as tempo and pattern. Both expert and non-expert jugglers juggled the standard and reverse cascade at

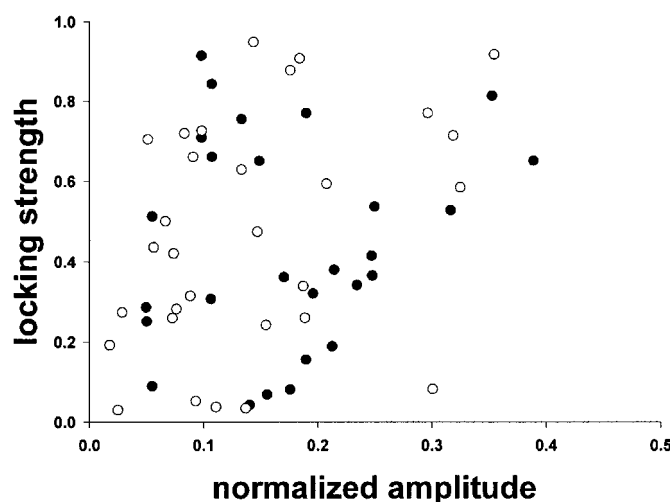


Fig. 10. Relation between the normalized amplitude of point-of-gaze movements and strength of frequency locking in the vertical direction as a function of expertise (in dimensionless units). Intermediates represented by solid circles, experts by open circles.

three self-selected tempos, with point-of-gaze and ball movements being recorded simultaneously. All gaze-related measures were characterized by considerable inter-individual variability. This is a well-known problem in visual search research that complicates the analysis and interpretation of the data (cf. Williams *et al.*, 1993). Nevertheless, we were able to verify the three expectations regarding the effects of expertise, tempo and pattern on the relation between point-of-gaze and ball movements in cascade juggling. In the following, we discuss our results in terms of these expectations. Subsequently, we conclude the article with a concise summary of our main findings as well as the theoretical implications of these findings for understanding the relations between visual search patterns, information pick-up, expertise and task performance in general.

Effects of expertise

The visual search behaviour of experts differs from that of non-experts in a variety of ways (Williams *et al.*, 1992; Bard *et al.*, 1994; Amazeen *et al.*, 2001). In juggling, we expected experts to exhibit more economical visual search patterns, earlier visual contact with the ball in flight (both in terms of phase and time to catch) and weaker frequency locking between point-of-gaze and ball movements. These expectations were confirmed only in part. Before discussing the results and their implications, we address the possible confounding of the effect of expertise by the effect of tempo.

This possibility occurred because expertise and tempo often had similar effects and the tempo conditions were more pronounced in the experts. There are three reasons to believe, however, that tempo did not, or at most only marginally so, confound the effects of expertise. First, across tempo conditions, experts and intermediates did not juggle at significantly different frequencies. Second, two significant interactions between tempo and expertise revealed different tempo effects for both expertise groups (normalized amplitude of point-of-gaze movements in the horizontal direction; percentage of intersections between the line of gaze and the balls). Thus, to the extent that the effect of expertise was confounded by the effect of tempo, the direction of this confounding was not always the same. Third, the intermediates performed worse than the experts, probably resulting in weaker frequency locking between point-of-gaze and ball movements. Although this effect was relatively small, it counteracted a possible confounding of the effect of expertise by the effect of tempo, at least for the dependent variable strength of frequency locking.

As expected, the visual search behaviour of the experts was more economical than that of the inter-

mediates. Experts made smaller gaze shifts, but only significantly so in the preferred and fast conditions. Furthermore, the experts kept their 'eyes on the ball' less often than the intermediates in the slow and preferred tempo conditions, which is consistent with other studies showing that certain expertise-related features are only revealed under certain task conditions (Ripoll *et al.*, 1995; Amazeen *et al.*, 2001). Finally, the incidence of 1:1 frequency locking in the horizontal direction was lower in the experts than in the intermediates (although the strength of this locking did not differ significantly between the two groups), whereas the incidence of 1:2 frequency locking in the vertical direction was higher in the experts than in the intermediates. Both these findings are consistent with the expectation that experts would adopt a more economical visual search behaviour, in that they traded a visual search pattern involving a direct coordination with the balls (1:1 frequency coordination) for one involving only an indirect (alternating) coordination with the balls (1:2 frequency coordination).

Contrary to our expectation, which was based on the results of previous research (Bard *et al.*, 1994; Amazeen *et al.*, 2001), the point-of-gaze data contained no evidence that the experts picked up information significantly earlier than the intermediates, either in terms of the introduced phase variable or in terms of the time to catch. This unexpected finding may have been due to the relatively large between-individual variability in both variables, but this cannot explain the differences with the results of Amazeen *et al.* (2001) because their data were also quite variable. We therefore consider it more likely that the absence of an effect of expertise on the phasing and timing of making visual contact with the balls is a consequence of the specific constraints imposed by the juggling task on visual search behaviour. When juggling three balls instead of one, there are often two airborne balls, one about to be caught, the other just released. As a consequence, picking up optical information from the just-thrown ball may interfere with picking up optical information from the still-to-be-caught ball of the previous toss and may, therefore, result in a deterioration in performance.

In combination, the findings for the effects of expertise suggest that the experts relied less on foveal vision and probably more on peripheral vision and kinaesthetic and haptic information than the intermediates. Thus, the overall impression from the observed visual search patterns is that vision is less critical for experts than for intermediates. This conclusion is consistent with the findings of Fleishman and Rich (1963) and Henderson (1975) but at odds with those of Proteau *et al.* (1987). In all likelihood, this discrepancy is due to the specific character of the aiming task studied by Proteau and colleagues. In juggling, the hands are usually not in view

and the observed differences in the size and patterning of point-of-gaze movements between the expert and intermediate jugglers may be interpreted to imply that the expert jugglers control their direction of gaze less than the intermediate jugglers. Experts, it would appear, become increasingly less dependent on visually tracking the motion of the balls, thus confining the control space of juggling more to variables associated with the hand movements (cf. Scholz and Schöner, 1999).

Effects of tempo

We expected increasing juggling frequency to result in weaker coupling between point-of-gaze and ball movements and in earlier intersections of the line of gaze with the trajectories of the balls, at least in terms of their phasing relative to the zenith. The former expectation was confirmed, whereas the latter was not.

The reciprocal relation between movement frequency and the stability of movement patterns has been well documented for inter-limb coordination (Kelso, 1995; Peper *et al.*, 1995). Increasing movement frequency has a destabilizing effect on inter-limb coordination and hence may induce transitions. The principle of frequency-induced destabilization was hinted at in the present experiment in that higher juggling tempos resulted in a weaker 1:1 frequency coupling between point-of-gaze and ball movements in the vertical direction. Increasing the frequency of juggling, however, also led to an increased incidence of the 1:2 mode locking, possibly accompanied by stabilization of this particular frequency lock. In the horizontal direction, increasing the tempo only tended to reduce the strength of the frequency locking in the standard cascade. It is probable that this effect would have been significant with more participants.

The increase in juggling frequency did not affect the pattern of the spectral estimates of the ball movements to such an extent that this could explain the observed mode-locking phenomena. Hence, these phenomena constituted truly different visual search patterns. Interestingly, the coordination between point-of-gaze and ball movements changed differentially as a function of increasing juggling frequency in the two dimensions of interest, which, in retrospect, justified our motivation to analyse point-of-gaze in two separate dimensions. This finding is consistent with evidence suggesting that the horizontal and vertical components of both saccadic and smooth pursuit eye movements have different neurophysiological underpinnings (Wirtschafter and Weingarden, 1988) and are, at least partially, dynamically independent (Becker and Jürgens, 1990). This interpretation was further supported by visual inspection of the gaze-tracker data (as projected in the images of the head-mounted video-camera), which revealed

a strong contribution of saccadic eye movements in the horizontal direction to point-of-gaze movements, whereas the distribution of saccadic and smooth pursuit eye movements in the vertical direction strongly depended on juggling frequency. These effects may well have been the result of the structural and functional differences that have been identified for the generation of horizontal and vertical eye movements, respectively. On the basis of the present results, however, this can only be a conjecture.

An increase in juggling frequency also resulted in more economical search patterns: as frequency increased, there was a reduced tendency to keep the 'eyes on the balls', whereas the incidence of 1:2 frequency locking in the vertical direction increased. This mode can be considered to be more economical because it involves fewer point-of-gaze movements and no direct mapping between direction of gaze and ball movements, as in the 1:1 frequency mode. Admittedly, the increase in frequency also resulted in longer dwell times ('time on ball'), but this effect should largely be ascribed to the reduction in the size of the ball pattern with increasing frequency. The smaller the juggle, the smaller the angle between the line of gaze and the floor (i.e. the more the juggler looks downward). The balls are then thrown into the line of sight, and the intersection of the line of gaze with the rising ball may last all the way from ball release to the instant the ball reaches its zenith. Consequently, the increased dwell times ('time on ball') with increasing frequency should be considered as a geometrical side-effect.

Contrary to our expectation based on previous research on the repetitive catching and throwing of a single ball (Amazeen *et al.*, 1999, 2001), an increase in juggling frequency did not result in significant shifts of the dependent variable relative phase. This suggests that the increase in juggling frequency did not lead to earlier pick-up of fine-grained optical information by the foveal system. This does not exclude, however, that optical information was picked up earlier by the parafoveal or peripheral system, or that other relevant information was picked up earlier by the kinaesthetic or haptic system with increasing juggling frequency. Unfortunately, such possibilities cannot be verified on the basis of the present results. It is probable that the absence of a significant effect of juggling frequency on the phase variable was due to the specific task constraints of three-ball cascade juggling, which require a time-dependent distribution of visual attention and, hence, a task-specific adaptation of the visual search behaviour (see next section). In addition, the large between-tempo condition variability of the phase variable, suggesting that large portions of the ball trajectories contain relevant information for juggling, may have prevented it from reaching significance.

The temporal window between the intersections of the line of gaze with the ball trajectories and the moments of the catches decreased with increasing juggling frequency, which is in line with the results of Amazeen *et al.* (2001). Presumably, this finding reflects the increasing temporal constraints brought about by increasing juggling frequency, in that juggling slowly allows for information pick-up earlier before the catch than is strictly necessary, which may no longer be beneficial when juggling fast, as this would interfere with attending to the previous toss.

In summary, the present results clearly demonstrate that the manipulation of tempo had a strong effect on the visual search patterns adopted. The observed disparity in the manner in which the direction of gaze was affected by tempo in the horizontal and vertical direction may have been due to different organizational principles underlying the execution of horizontal and vertical eye movements, respectively.

Effects of pattern

The expectation that the frequency locking between point-of-gaze and ball movements would be stronger in the reverse cascade than in the standard cascade was confirmed for the horizontal direction. In addition, larger gaze shifts were made and the line of gaze intersected both later and more often with the balls in the reverse than in the standard cascade.

The differences in the normalized amplitude of the point-of-gaze movements between the standard and reverse cascade can probably be explained by their spatial properties. Recall that normalization of the gaze shifts was related to the zeniths. Although the horizontal distance between the zeniths and the height of the throws (to the zenith) characterize the juggling pattern, these are not the only factors to distinguish the two juggling patterns spatially. The angle of release (referenced to the vertical) of the thrown balls and the velocity in the horizontal direction are greater in the reverse cascade than in the standard cascade. Because there was no significant difference between the two juggling patterns for the time the 'eyes were on the ball', tracking the ball for a given time resulted in larger point-of-gaze movements in the reverse than in the standard cascade.

In the horizontal direction, the gaze shifts were more strongly frequency-locked to the ball movements in the reverse than in the standard cascade. Furthermore, the line of gaze intersected more often with the balls. Given the visual acuity of the eyes, this result implies that the participants required more finer-grained optical (i.e. foveal) information to juggle the reverse cascade than to juggle the standard cascade. In addition, both in terms of the phase variable and the time to catch, foveal information pick-up occurred later in the reverse than

in the standard cascade. These results, as well as the tendency for a significant tempo \times pattern interaction effect on the strength of mode locking in the horizontal direction, demonstrate that the pattern manipulation strongly affected the visual search patterns adopted. This supports our premise that visual search should be studied in the context of the action it supports. (Because the participants are likely to have practised the reserve cascade considerably less often than the standard cascade, which is the pattern a novice juggler will typically begin with when learning to juggle, the observed effects of pattern could have been confounded by the factor 'expertise'. However, considering that the visual search-related measures differed much more as a function of pattern than of expertise, it is likely that the observed effects of pattern were, at least to some extent, true pattern effects.)

Conclusion

Juggling involves a variety of visual search patterns, ranging from large horizontal gaze shifts to small changes in point-of-gaze within a confined fixation area. The line of gaze did not always intersect with the ball, suggesting that the pick-up of very precise optical information by the fovea is not necessary and that para-foveal and peripheral vision often suffice. Although the phase at which the balls were viewed relative to the zenith of their trajectories did not depend on juggling frequency, it would be incorrect to conclude that the balls have to be viewed at a particular location along their flight trajectories. The large standard deviations of the viewing phase suggest that, in principle, many segments of the flight trajectories carry useful optical information for sustaining the juggle (cf. Van Santvoord and Beek, 1994). The most salient result of the present study was the regular occurrence of two modes of frequency locking between point-of-gaze and ball movements: 1:1 frequency locking prevailed in the horizontal dimension, whereas 1:1 and 1:2 frequency locking occurred about equally often in the vertical dimension. Although these modes of locking occurred largely irrespective of the amplitude of the point-of-gaze movements, the visual search patterns adopted were affected by the expertise of the participant (expert *vs* intermediate) and by task manipulations related to tempo and pattern.

The expert jugglers performed better than their intermediately skilled counterparts, while showing more restricted, economical visual search patterns. Although in both directions the strength of the observed frequency locking did not depend on expertise, the experts showed less frequency locking in the horizontal direction than the intermediates. In the vertical direction,

the experts adopted 1:2 frequency locking more often and 1:1 frequency locking less often than the intermediates. These findings suggest that experts depend less on foveal vision and more on peripheral vision and kinaesthetic and haptic information than intermediates. This conclusion is consistent with the often quoted but seldom empirically corroborated insight that the acquisition of perceptual-motor skills may involve qualitative shifts (from foveal vision to peripheral vision and from peripheral vision to kinaesthesia) in the relative importance of the various perceptual (sub)systems for skill performance.

Tempo affected the observed visual search patterns: increasing the juggling frequency resulted in a lower incidence of 1:1 frequency locking but in a higher incidence of 1:2 frequency locking in the vertical direction. Only the strength of the 1:1 mode locking decreased with increasing tempo. Furthermore, increasing juggling frequency resulted in fewer intersections of the line of gaze with the ball; however, when there was such an intersection, more time was spent with the 'eyes on the ball'. In general, the findings for the effect of tempo are consistent with a key insight in the study of rhythmic bimanual coordination from a dynamical systems perspective – namely, that the interaction between two coupled subsystems decreases as their frequency of operation increases.

In the reverse cascade, larger gaze shifts were made in both directions than in the standard cascade, but only in the horizontal direction were the point-of-gaze movements more strongly mode-locked to the ball movements. In addition, optical information was picked up foveally later in the reverse cascade than in the standard cascade. The strong effects of the task constraints brought about by tempo and pattern on visual search behaviour highlight the importance of studying visual search in the context of the task it subserves.

Finally, the method adopted in the present study has been shown to be well-suited to both qualify and quantify the manner in which patterns of visual search are embedded in the performance of a particular perceptual-motor task while incorporating the task constraints. How this embedding evolves in the acquisition of a particular task, however, cannot be deduced from the present results. Finding an answer to this question would deepen our insights into both visual search behaviour and expertise. This has motivated us to conduct a longitudinal learning study using this method in the near future.

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